Extractive Metallurgy of Copper

Sixth Edition

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Preface to the sixth edition

When we began this revision in 2019, the price of copper was $2.60/lb. As we complete it today, the price is $4.38/lb. By the time you read these words, it may be back down to $2.60 again! Regardless, it has been some time since there was so much interest in the availability and technology of copper supply. The long-term prospects for the industry appear to be bright, and prospectors are scouring the globe for ore, from mountaintops in the Andes to the bottom of the oceans. The lists of top-producing mines and smelters in this book demonstrate the increase in capacity of the industry from our previous edition.

Technology advances in the industry over the previous decade have been largely evolutionary rather than revolutionary. The most significant developments include the following:

- the adoption of Chinese bottom-blown and side-blown bath smelting and converting technology;
- the creation of flowsheets for handling increasingly complex ores and concentrates;
- improved technology for processing high-strength off-gases;
- higher current densities in electrorefining and electrowinning practice.

Other things have not changed. The Peirce–Smith converter is still the primary means of producing blister copper; flash furnaces are still being commissioned for concentrate smelting, and casting processes are still largely the same. Some technologies have more value than previously thought!

There has also been a change in the creative team behind this book. Matt King has decided to find other uses for his nights and weekends; in his place, we welcome to the group Dr. Gerardo Alvear Flores, currently based in Singapore. Gerardo has vast experience in the copper industry, which has taken him over his career to multiple continents and production facilities, and his experience will enhance our efforts and improve our direction.

As with previous efforts, this edition of *Extractive Metallurgy of Copper* is largely a product of the copper industry as a whole, since so many engineers and scientists volunteered their time and expertise (along with photographs and drawings) to make sure we got it right. Our guides included

Ken Armstrong (Chemetics)
Nigel Aslin (Glencore)
Martin Bakker (Glencore)
Michele Beacom (CIM)
Juan Carrasco (Glencore)

Chunlin Chen (CSIRO)
Peter Cole (deceased) (Peter Cole Metallurgical Services)
Bernadette Currie (Rio Tinto)
Julio Flores Cantillánez (Mantos Copper)
Magnus Ek (Boliden)
Jeremy Gillis (PASAR)
Cameron Harris (Canadian Engineering Associates)
David Hazelett (Hazelett Corporation)
Enrique Herrera (Southern Peru Copper)
Shawn Hinsberger (Heath and Sherwood)
Mike Hourn (Glencore)
Chris Holding (Copper Worldwide)
John Hugens
John Hugens, Jr. (Hugens Metallurgy)
Evgeni Jak (University of Queensland)
Hugo Joubert (Tenova Pyromet)
Akira Kaneda (Mitsubishi Materials)
Matt King (Worley Parsons)
Michael Marinigh (Heath and Sherwood)
Leopoldo Mariscal (Mexicana de Cobre)
Jorge Meza (Southern Peru Copper)
Yoshihiro Mine (Mitsui Mining & Smelting)
Enrique Miranda (IIMCH)
Michael Moats (Missouri University of Science and Technology)
Anthony Mukutuma (First Quantum Minerals)
Kensaku Nakamura (JX Nippon Mining and Metals)
Takeshi Nakamura (Tohoku University)
Stanko Nikolic (Glencore)
Yerzhan Ospanov (Kazakhmys)
Lauri Palmu (Metso Outotec)
John Parker (Process Ideas)
Joe Pease (Minerales)
Beatrice Pierre (Glencore)
Nikola Popovic (Glencore)
Yves Prevost (Glencore)
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Pedro Reyes (Anglo American)
Carlos Risopatron (International Copper Study Group)
Joanne Roberts (Freeport McMoRan)
Tim Robinson (Metso Outotec)

Gerardo Sanchez (Codelco)
Maxsym Shevchenko (University of Queensland)
Etsuro Shibata (Tohoku University)
Denis Shishin (University of Queensland)
Alfred Spanring (RHI AG)
Andreas Specht (Aurubis)
Hitoshi Takano (Sumitomo)
Supriya Upadhyay (Rio Tinto)
Maurits Van Camp (Umicore Precious Metals Recycling)
Nicole Witaslawsky (International Copper Association)
Yutaka Yasuda (JX Nippon Metals and Mining)
Gabriel Zárate (Jetti Cobre)

CHAPTER 1

Overview

1.1 Introduction

Copper is most commonly present in the earth's crust as copper—iron—sulfide and copper sulfide minerals, primarily chalcopyrite ($CuFeS_2$) and chalcocite (CuS_2). The concentration of these minerals in a mine is low. Typical copper ores contain from 0.3% Cu (open pit mines, Fig. 1.1) to 1.7% Cu (underground mines, Fig. 1.2). The rest is noneconomic rock. Pure copper metal is mostly produced from these ores by concentration, smelting, and refining (Fig. 1.3).

Copper also occurs to a lesser extent in oxidized minerals (carbonates, oxides, hydroxysilicates, sulfates). Copper metal is usually produced from these minerals by leaching, solvent extraction, and electrowinning (Fig. 1.4). These processes are also used to treat chalcocite (Cu_2S).

Figure 1.1 Open pit Cu mine. Note the new blast holes, top right, and blasted ore to the left of them. The shovel is placing blasted ore in the truck from where it will go to processing. The water truck is suppressing dust. The front-end loader is cleaning up around the shovel. The shovel is electric. Its insulated power wire mostly lies on the surface except over the wire bridge under which all vehicles travel to and from the shovel. *(Photograph courtesy of Freeport—McMoRan Copper & Gold Inc.)*.

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Figure 1.2 Underground mining operation. Underground mine showing wheeled mining machine. The drills on the right end of the vehicle are drilling up into the ore body. The drilled holes are subsequently filled with explosive which, when detonated, break the ore and drop the ore pieces onto the mine floor. The ore pieces are then elevated to the mine surface where they are crushed and sent to processing. A new mine in Arizona contains ~1.5% Cu, 0.04% Mo in chalcopyrite and molybdenite minerals. ~120 kilotonnes per day of this ore will be mined ~2300 m below ground level. About one-fourth of the world's mined copper is obtained by underground mining; the remainder is by surface mining. *(Purchased from Roslyn Budd: www.buddphotography.com.au).*

A third major source of copper is scrap copper and copper alloys. Yearly production of copper from recycled used objects is 15%–20% of mine production. In addition, there is considerable remelting and refining of scrap generated during fabrication and manufacture. Total copper production in 2018 (mined and from end-of-use scrap) was 25 million tonnes.

This chapter introduces the principal processes by which pure copper is extracted from ore and scrap. It also indicates the relative industrial importance of each. Finally, it discusses worker safety—because it is so important.

1.2 Ore–rock differentiation in the mine

A mine consists of regions of economic ore and regions of noneconomic rock, e.g., quartz and feldspar (Berger et al., 2008). These regions are located by drilling, sampling, and analyzing the drill core for Cu. Where possible the noneconomic rock is not mined. When the mine can only be developed by mining intertwined ore and rock, the ore is sent to copper production and the rock goes to waste heaps. The material at the ore/rock boundary is carefully sampled and analyzed to ensure that ore is not mistakenly sent to the waste rock heaps.

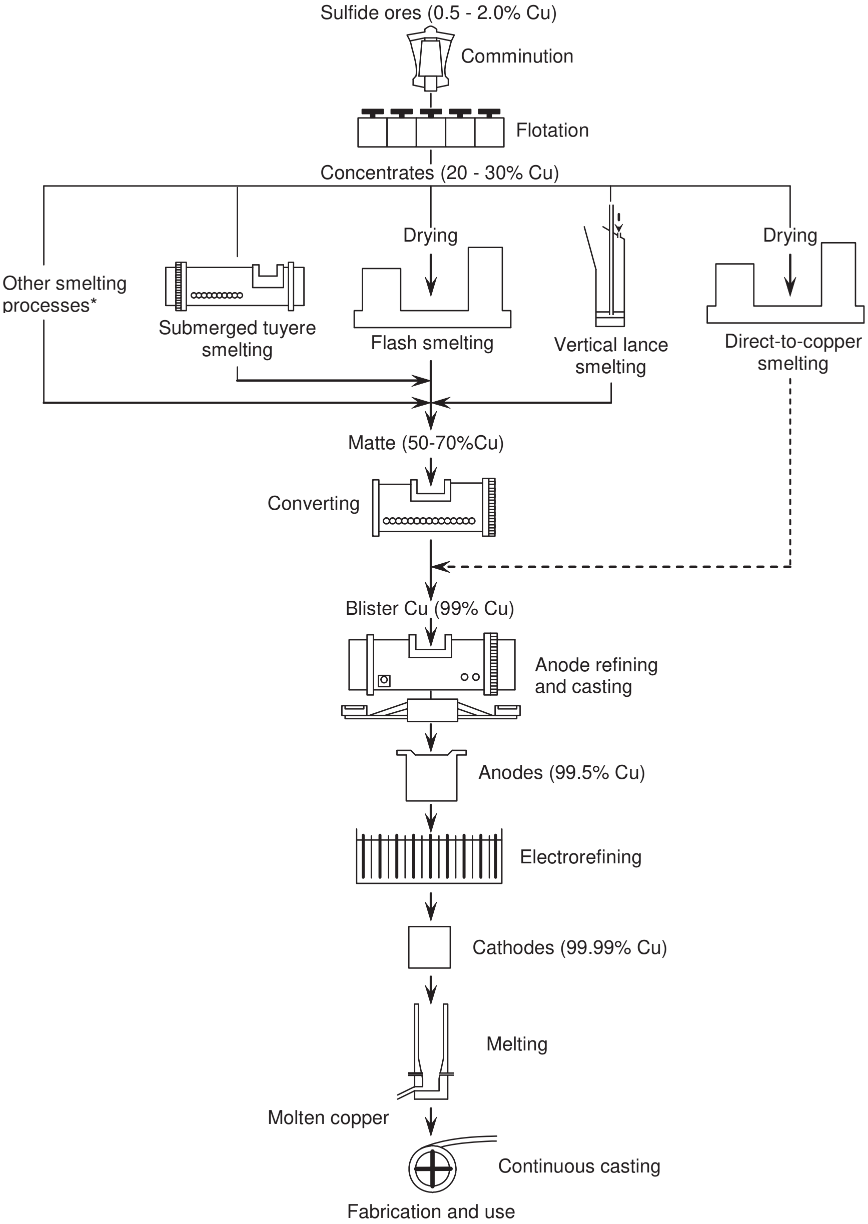

Figure 1.3 Main processes for extracting copper from sulfide ores. *Parallel lines* indicate alternative processes. *Principally Mitsubishi and Vanyukov smelting. ——————and various small Chinese processes.

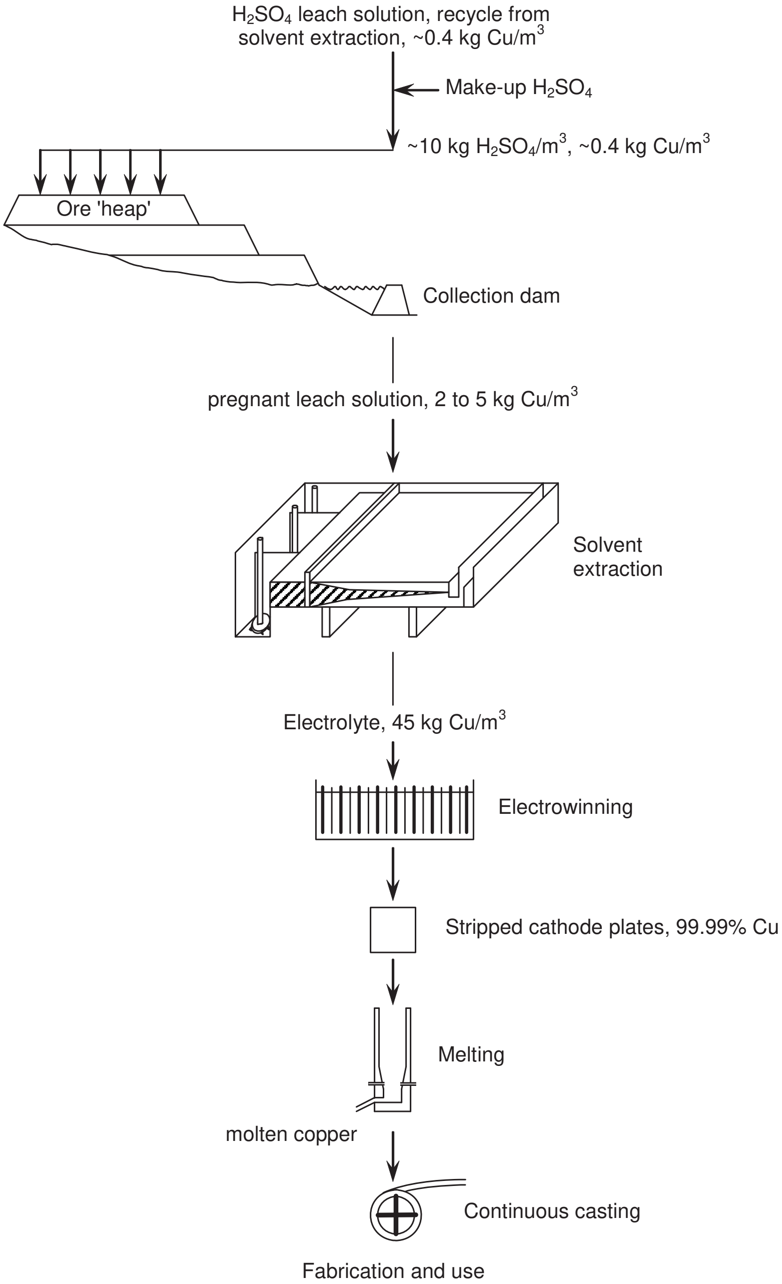

Figure 1.4 Flowsheet for leaching oxide and Cu_2S ores. The dissolved Cu is recovered by solvent extraction purification followed by electrowinning. Leaching accounts for ~20% of primary (from ore) copper production.
]

1.3 Extracting copper from copper–iron–sulfide ores

About 80% of the world's mined copper originates in chalcopyrite ($CuFeS_2$) ores. Chalcopyrite is extremely difficult to dissolve in aqueous solutions, so the vast majority of copper extraction from these ores is pyrometallurgical. Extraction by this approach entails

- **(a)** isolating the ore's Cu–Fe–S and Cu–S mineral particles in a concentrate by froth flotation
- **(b)** smelting this concentrate to molten high-Cu sulfide *matte*
- **(c)** converting (oxidizing) this molten matte to impure molten *blister* copper
- **(d)** fire- and electrorefining this impure copper to ultrapure copper.

Increasingly, smelting and converting are being combined, especially in China.

1.3.1 Concentration by froth flotation

Copper ores being mined in 2020 are far too dilute in Cu (0.3%–1.7%) to be smelted directly. Heating and melting their huge quantity of waste rock would require prohibitive amounts of fuel. The rock would also produce impossibly large amounts of molten oxide slag. Fortunately, the ore's Cu–Fe–S and Cu–S minerals can be isolated by physical means into high-Cu concentrate, which can then be smelted economically.

The most effective method of isolating the Cu minerals is froth flotation. This process causes small Cu–Fe–S and Cu–S mineral particles to become attached to air bubbles rising through a finely ground ore slurry (Fig. 1.5). Selectivity of flotation is created by

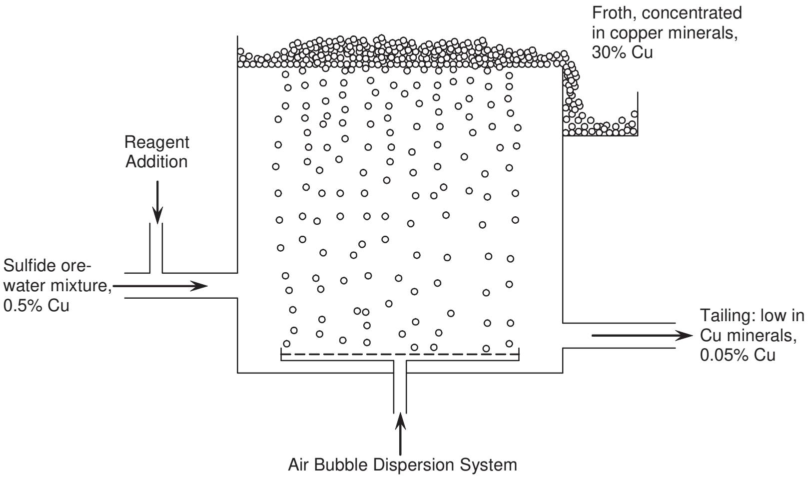

Figure 1.5 Schematic view of flotation cell. Reagents cause Cu–Fe sulfide and Cu sulfide minerals in the ore to attach to rising air bubbles, which are then collected in a short-lived froth. This froth is dewatered to become concentrate. The unfloated waste passes through several cells before being discarded as a final tailing. Many types and sizes (up to 300 m^3) of cell are used (Chapter 3).

using chemical reagents (collectors) that make the Cu minerals water-repellent while leaving waste minerals covered by water (i.e., wetted).

This water repellency causes Cu mineral particles to attach to the flotation cell's rising bubbles while the other mineral particles remain unfloated. The floated minerals overflow the cell in a froth that, when dewatered, becomes ~25% Cu *concentrate*. The low-Cu waste rock particles underflow the cell. They are dewatered and sent to tailing ponds.

Flotation is preceded by crushing and grinding the mined Cu ore to small (~100 μm diameter) particles. Its use has led to adoption of smelting processes that efficiently smelt finely ground solids.

A video of mining and mineral processing may be seen in *The Mining Process at Copper Mountain Mine*. This mine produces 30,000 tonnes of ore and 160,000 tonnes of waste rock per day.

1.3.2 Matte smelting

Matte smelting oxidizes and melts flotation concentrate in a large, hot (1250°C) furnace (Figs. 1.3 and 1.6). The objective of the smelting is to oxidize S and Fe from the Cu—Fe—S concentrate to produce an intermediate Cu-enriched molten sulfide matte. The oxidant is oxygen-enriched air. Example reactions are

$$\underset{\text{in concentrate}}{\overset{30\ ^\circ\text{C}}{2\ \mathrm{CuFeS_2(s)}}} + \underset{\text{in oxygen–enriched air}}{3.25\ \mathrm{O_2(g)}} \rightarrow \underset{\text{molten matte}}{\overset{1220\ ^\circ\text{C}}{\mathrm{Cu_2S\text{-}0.5FeS}(\ell)}} + \underset{\text{iron oxide}}{1.5\ \mathrm{FeO(s)}} + \underset{\text{in offgas}}{2.5\ \mathrm{SO_2(g)}} \tag{1.1}$$

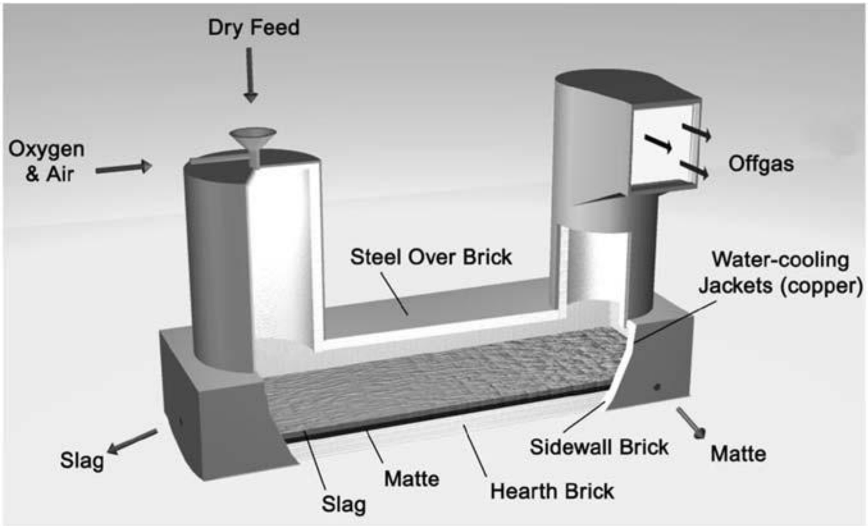

Figure 1.6 Metso Outokumpu oxygen-enriched air flash furnace. Flash furnaces are typically 20 m long and 7 m wide. They smelt 1000—3000 tonnes of concentrate per day.

Simultaneously, the iron oxide is fluxed with quartz to give a low melting point molten slag. A representative reaction is

$$\underset{\text{iron oxide}}{\overset{1220\ ^\circ\text{C}}{1.5\ \text{FeO(s)}}} + \underset{\substack{\text{in rock and}\\ \text{quartz flux}}}{\overset{30\ ^\circ\text{C}}{0.75\ \text{SiO}_2\text{(s)}}} + \text{heat} \rightarrow \underset{\text{molten slag}}{\overset{1250\ ^\circ\text{C}}{0.75\ \text{Fe}_2\text{SiO}_4(\ell)}} \tag{1.2}$$

The concentrate's *gangue* (waste rock) minerals also dissolve in the molten slag.

Reactions (1.1) and (1.2) are both exothermic; they supply most of the smelting process's heat requirement.

The products of smelting are (a) molten sulfide matte (55%–70% Cu) containing most of the Cu in the concentrate and (b) molten oxide slag with as little Cu as possible. The molten matte is subsequently converted (oxidized) in a converting furnace to form impure molten copper. The slag is treated for Cu recovery, then discarded or sold (Chapter 10).

SO_2-bearing offgas (10–60 volume% SO_2, remainder mostly N_2) is also produced. SO_2 is harmful to flora and fauna, so it must be removed before the offgas is released to the atmosphere. This is done by capturing the SO_2 as sulfuric acid (Chapter 11).

Matte smelting is mostly done in flash furnaces (Fig. 1.6). It is also done in top lance and submerged tuyere furnaces (Chapter 6). Three smelters smelt Cu-rich concentrate directly to molten copper (Chapter 10). This is unusual because single-furnace smelting with normal (25% Cu) concentrate produces too much high-Cu slag.

1.3.3 Converting

Copper converting is oxidizing the intermediate molten matte from smelting with air or oxygen-enriched air. It removes Fe and S from the matte to produce crude (99% Cu) molten copper. This molten copper is subsequently sent to fire- and electrorefining.

Most converting is done in cylindrical Peirce–Smith converters (Fig. 1.7a), but newer continuous converting processes are eating into this dominance (Chapter 8).

1.3.3.1 Peirce–Smith converting

Peirce–Smith converting entails pouring large ladles of molten smelting furnace matte (1220°C) into a cylindrical converter through a large central mouth (Fig. 1.7b). The oxidizing oxygen-enriched air *blast* is then started and the converter is rolled, forcing the blast into the molten matte through a row of tuyeres along the length of the vessel. The heat generated in the converter by Fe and S oxidation is sufficient to make the process autothermal.

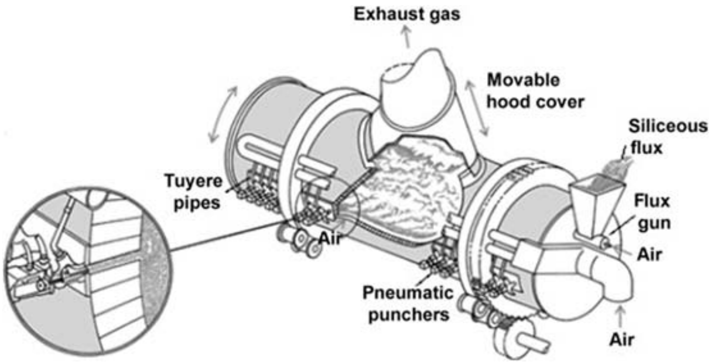

Figure 1.7a Peirce—Smith converter for producing molten "blister" copper from molten Cu—Fe—S matte. Typical production rates are 200—600 tonnes of copper per day. Oxygen-enriched air or air "blast" is blown into the matte through submerged tuyeres. Silica flux is added through the converter mouth or by air gun through an endwall. Offgas is collected by means of a hood above the converter mouth. *(From Chapter 2.1 - Copper Production in Treatise on Process Metallurgy, Volume 3: Industrial Processes, 1st Edition, Copyright Elsevier 2013 Pages 534—624).*

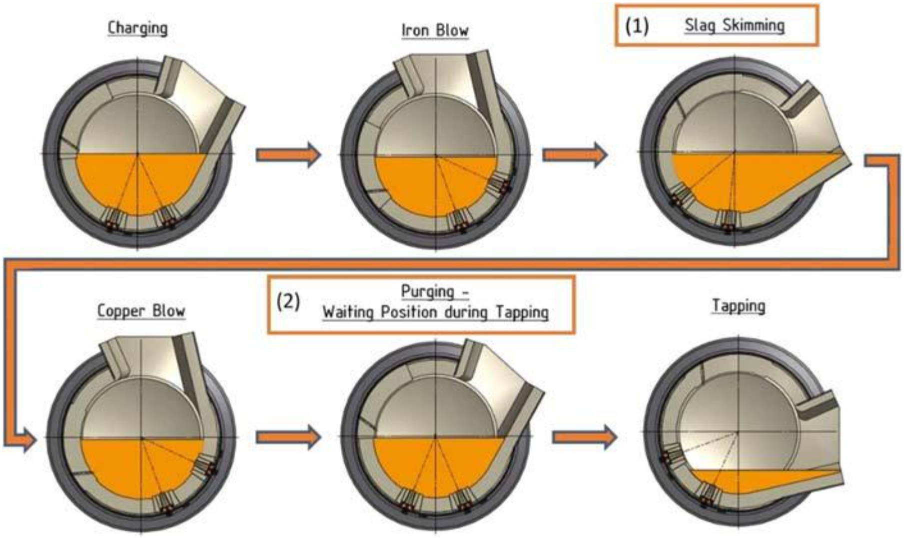

Figure 1.7b Positions of Peirce—Smith converter for charging, blowing, and skimming. SO_2 offgas escapes the system unless the hooding is tight. A converter is typically 4 or 4.5 m diameter. *(Credit: Used with permission from Mettop, https://mettop.com/api/cdn/uploads/1493364462_7v372frw.pdf Figure 4).*

The converting takes place in two sequential stages:

(a) the FeS elimination or slag-forming stage:

$$\underset{\text{in molten matte}}{\overset{1220\ °C}{2\,FeS(\ell)}} + \underset{\text{in air blast}}{\overset{30\ °C}{3\,O_2(g)}} + \underset{\text{in quartz flux}}{\overset{30\ °C}{SiO_2(s)}} \rightarrow \underset{\text{molten slag}}{\overset{1200\ °C}{Fe_2SiO_4(\ell)}} + \underset{\text{in offgas}}{\overset{1200\ °C}{2\,SO_2(g)}} + \text{heat} \tag{1.3}$$

(b) the copper-making stage:

$$\begin{array}{ccccccccc} 1200\ ^\circ\mathrm{C} & & 30\ ^\circ\mathrm{C} & & 1200\ ^\circ\mathrm{C} & & 1200\ ^\circ\mathrm{C} & & \\ Cu_2S(\ell) & + & O_2(g) & \rightarrow & 2\ Cu(\ell) & + & SO_2(g) & + & \text{heat} \\ \text{molten matte} & & \text{in air blast} & & \text{impure molten} & & \text{in offgas} & & \\ & & & & \text{'blister' copper} & & & & \end{array} \tag{1.4}$$

Copper making (b) occurs only after the matte contains less than about 1% Fe, so that most of the Fe can be removed from the converter (in slag) before copper production begins. Likewise, significant oxidation of copper does not occur until the sulfur content of the copper falls below ~0.02%. Blowing is terminated near this sulfur end point. The resulting molten blister copper (1200°C) is poured out and sent to refining, whereupon the converter is refilled with molten matte and the process starts again.

Because conditions in the converter are strongly oxidizing and agitated, Peirce–Smith converter slag inevitably contains 4%–8% Cu. This Cu is recovered by settling and/or ambient temperature froth flotation. The resulting low-Cu slag is then discarded or sold (Chapters 10 and 20).

SO_2, 8–12 vol.% in the converter offgas, is a byproduct of both converting reactions. It is combined with smelting furnace gas and captured as sulfuric acid. There is, however, some leakage of $SO_2(g)$ into the atmosphere during charging and pouring. This problem is encouraging development of continuous converting processes. The most prominent of these is *flash converting* (Chapter 8).

1.3.4 Direct-to-copper smelting

Smelting and converting are sequential steps in oxidizing Cu–Fe–S concentrates to metallic copper. It would seem natural that these two steps should be combined to produce *blister* copper directly in one furnace. It would also seem natural that this should be done continuously rather than batchwise.

In 2020, *blister* copper is made in a single furnace at only three places—Olympic Dam, Australia; Glogow, Poland; and Chingola, Zambia—all using a flash furnace. The strong oxidizing conditions in a direct-to-copper furnace produce a slag with 14%–24% oxidized Cu. The expense of reducing this dissolved Cu back to copper metal has so far restricted the process to low-Fe concentrates, which produce little slag.

Continuous smelting/converting, even in more than one furnace, has energy, SO_2 collection, and cost advantages. Metso Outotec flash, Mitsubishi lance, and Noranda submerged-tuyere smelting/converting all use this approach, described in Chapter 6 through Chapter 8.

1.3.5 Fire refining and electrorefining of blister copper

The *blister* copper from the above processing is electrochemically refined to high-purity cathode copper. This final copper contains less than 20 ppm undesirable impurities. It is suitable for electrical and almost all other uses.

Electrorefining requires strong, thin, flat anodes to interleave with cathodes in an electrorefining cell, Fig. 1.8. These anodes are produced by (a) sequential air oxidation then natural gas reduction of blister copper then (b) casting the resulting *fire-refined* copper in open, anode-shape molds (Figs. 12.2 and 12.3.).

Copper electrorefining entails

(a) electrochemically dissolving copper from fire-refined anodes into $CuSO_4-H_2SO_4-H_2O$ electrolyte

(b) electrochemically plating pure copper (without the anode impurities) from the electrolyte onto stainless-steel cathodes by passing DC electrical current through the electrolyte between anodes and cathodes.

Copper is deposited on the cathodes for 7—14 days. The cathodes are then removed from the cell. The copper is stripped, washed, and (a) sold or (b) melted and cast into useful products.

The electrolyte is an aqueous solution of H_2SO_4 (150—200 kg/m^3) and $CuSO_4$ (40—50 kg Cu/m^3). In use, it also contains impurities and trace amounts of chloride and organic *addition agents*, Section 14.5.1.

Figure 1.8 Casting of anodes for electrorefining. *(Photo courtesy of Miguel Palacios.).*

Many anode impurities are insoluble in this electrolyte (Au, Pb, Pt metals, Sn). They do not interfere with the electrorefining. They are collected as solid *slimes* and treated for Cu and byproduct recovery, Chapter 20.

Other impurities, such as As, Bi, Fe, Ni, and Sb, are partially or fully soluble. Fortunately, they do not plate with the copper at the low voltage of the electrorefining cell (~0.3 V). They must, however, be kept from accumulating in the electrolyte to avoid physical contamination of the cathode copper. This is done by continuously bleeding part of the electrolyte through a purification circuit.

An older form of the process is to plate cathode copper onto thin pure copper sheets. In this case the entire cathode is lifted from the cell, washed, and sent to users.

1.4 Hydrometallurgical extraction of copper

About 80% of copper from ore is produced by flotation, smelting, and refining. The remaining 20% is produced hydrometallurgically. Hydrometallurgical extraction entails (Fig. 1.3)

(a) sulfuric acid leaching of Cu from broken or crushed ore to produce impure Cu-bearing aqueous solution
(b) transfer of Cu from the resulting weak, impure solution to pure, high-Cu-strength electrolyte via solvent extraction
(c) electrodepositing pure cathode copper sheets from this pure electrolyte

The ores most commonly treated this way are (a) naturally oxidized Cu minerals, including carbonates, hydroxy-silicates, sulfates, and (b) chalcocite, Cu_2S.

The leaching is mostly done by dripping dilute sulfuric acid (~10 kg H_2SO_4 per m^3 of solution) onto a layer of broken or crushed ore (0.3%–2.3% Cu) and allowing the acid to trickle through to collection ponds, Figs. 1.4 and 1.5. Several months of leaching are required for efficient Cu extraction from the ore.

After this first extraction another layer of ore is placed on top of the leached layer and the process is repeated and so on.

Oxidized minerals are dissolved by the sulfuric acid by reactions like

$$\underset{\text{in ore}}{CuO(s)} + \underset{\text{in 30 °C sulfuric acid}}{H_2SO_4(\ell)} \rightarrow \underset{\text{aqueous pregnant leach solution}}{Cu^{2+}(aq) + SO_4^{2-}(aq) + H_2O(\ell)} \tag{1.5}$$

Sulfide minerals, on the other hand, require oxidation, schematically:

$$\underset{\text{in ore}}{Cu_2S(s)} + \underset{\text{in air}}{2.5O_2(g)} + \underset{\text{in sulfuric acid}}{H_2SO_4(\ell)} \xrightarrow[\text{30 °C}]{\text{bacterial enzyme catalyst}} \underset{\text{pregnant leach solution}}{2Cu^{2+}(aq) + 2SO_4^{2-}(aq) + H_2O(\ell)} \tag{1.6}$$

As indicated, sulfide leaching is greatly speeded up by bacterial action (Chapter 15).

Leaching is occasionally applied to Cu-bearing flotation tailings, mine wastes, old mines, and fractured ore bodies. However, leaching of ore heaps is far and away the largest hydrometallurgical Cu extraction technique.

1.4.1 Solvent extraction

The solutions from heap leaching contain ~3 g/L of Cu and ~3 g/L of H_2SO_4 plus dissolved impurities, such as Fe and Mn. These solutions are too dilute in Cu and too impure for direct electrodeposition of pure copper metal. The Cu must be transferred to pure, high-Cu electrolyte to make pure copper.

The transfer is achieved by

(a) extracting Cu from an impure leach solution into a Cu-specific liquid organic extractant

(b) separating by gravity the Cu-loaded extractant from the Cu-depleted leach solution

(c) stripping Cu from the loaded extractant into 180 g/L H_2SO_4 electrolyte.

Extraction and stripping are carried out in large mixer-settlers, Fig. 1.9.

The solvent extraction process is represented by the reaction:

$$\underset{\text{in pregnant leach solution}}{Cu^{2+}(aq) + SO_4^{2-}} + \underset{\text{in organic solvent}}{2RH} \xrightarrow{30\ ^\circ C} \underset{\text{in organic solvent}}{R_2Cu} + \underset{\substack{\text{in aqueous solution,}\\ \text{recycle to leach}}}{2H^+ + SO_4^{2-}} \tag{1.7}$$

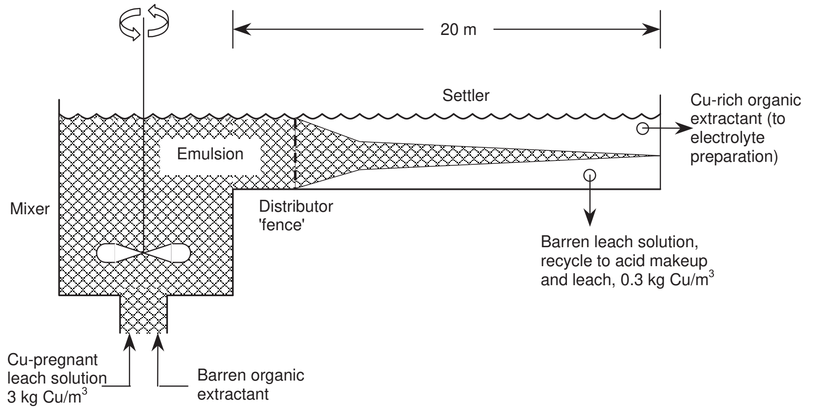

Figure 1.9 Schematic view of solvent extraction mixer-settler for extracting Cu from pregnant leach solution into organic extractant. The Cu-loaded organic phase goes forward to another mixer/setter ("stripper") where Cu is stripped from the organic into pure, strongly acidic, high-Cu electrolyte for electrowinning. The process is continuous.

This shows that a low-acid (i.e., low H^+) aqueous phase causes the organic extractant to load with Cu (as R_2Cu). It also shows that a strong acid solution causes the organic to unload (i.e., *strip*).

Thus, when organic extractant is contacted with weak acid pregnant leach solution [step (a) above], Cu is loaded into the organic phase. Then when the organic phase is subsequently put into contact with high (~180 g/L) H_2SO_4 electrolyte [step (c) above], the Cu is stripped from the organic into the electrolyte at high Cu^{2+} strength, suitable for electrowinning.

The extractants complex with considerable Cu but almost no impurities. They produce electrolytes that are strong in Cu (~50 g/L) but dilute in impurities.

1.4.2 Electrowinning

The Cu in the above electrolytes is mostly recovered by electrodepositing pure metallic copper onto stainless-steel cathodes, Fig. 1.10. Electrowinning is similar to electrorefining except that the anode is inert, almost always 99% Pb alloy.

The cathode reaction is

$$\underset{\text{in sulfate electrolyte}}{Cu^{2+}(aq)} \quad + \quad \underset{\substack{\text{electrons from}\\ \text{external DC power supply}}}{2e^-} \quad \xrightarrow{60\ ^\circ C} \quad \underset{\substack{\text{pure metal deposit}\\ \text{on stainless steel cathode}}}{Cu(s)} \tag{1.8}$$

Figure 1.10 Plates of electrowon copper on stainless-steel cathodes after removal from an electrowinning cell. These cathodes are ~1 m wide and 1.3 m deep. They are carefully washed to remove electrolyte. The copper plates are then stripped off in automatic machines and sent to market. They typically contain <20 parts per million impurities. Note the polymer side strips—they prevent copper from plating around the edges. *(Photograph courtesy of Freeport-McMoRan Copper & Gold Inc).*

The anode reaction is

$$\underset{\text{in electrolyte}}{H_2O(\ell)} \xrightarrow{60\,^{\circ}\text{C}} \underset{\substack{\text{evolved on}\\ \text{inert anode}}}{0.5\,O_2(g)} + \underset{\substack{\text{formed in electrolyte,}\\ \text{recycle to solvent}\\ \text{extraction}}}{2\,H^+(aq)} + \underset{\substack{\text{electrons to}\\ \text{external DC}\\ \text{power supply}}}{2\,e^-} \qquad (1.9)$$

As with electrorefining, the copper is plated on the cathode by passing DC current through the electrolyte between anodes and cathodes. About 2 V is required.

Pure metallic copper (less than 20 ppm undesirable impurities) is plated on the cathode. Oxygen gas is evolved at the anode.

A recent development is the use of precious metal-coated titanium cathodes, which lowers electrowinning energy consumption.

1.5 Melting and casting cathode copper

The first steps in making products from electrorefined and electrowon copper are melting and casting, Fig. 1.11. The melting is almost always done in vertical shaft furnaces, Fig. 19.2. The copper cathode sheets are charged to the top of the furnace. They descend into the furnace and are melted by ascending hot combustion gases. Low-sulfur fuels prevent sulfur pickup. Reducing flames prevent excessive oxygen pickup.

The molten copper is mostly cast in continuous casting machines from where it goes to rolling or extrusion then manufacturing. An especially important combination is continuous bar casting/rod rolling, Chapter 19.

1.5.1 Types of copper product

The copper described above is Grade 1 copper. It contains ~0.025% oxygen and the cathode impurities. It is the most common type of primary copper product.

A second type is oxygen-free copper (<5 ppm O). It is used for highly demanding applications, such as high-end audio equipment. It is made from cathode copper by electric induction melting with added pure graphite for removing O as CO(g).

About 35% of copper is used in alloy form as brasses, bronzes, etc. Much of the copper for these alloys comes from recycle scrap.

1.6 Recycle of copper and copper alloy scrap

Copper production from recycling copper and copper alloy end-of-life objects (*old* scrap) amounts to 15%–20% of the above-described copper-from-mine production (International Copper Study Group, 2020).

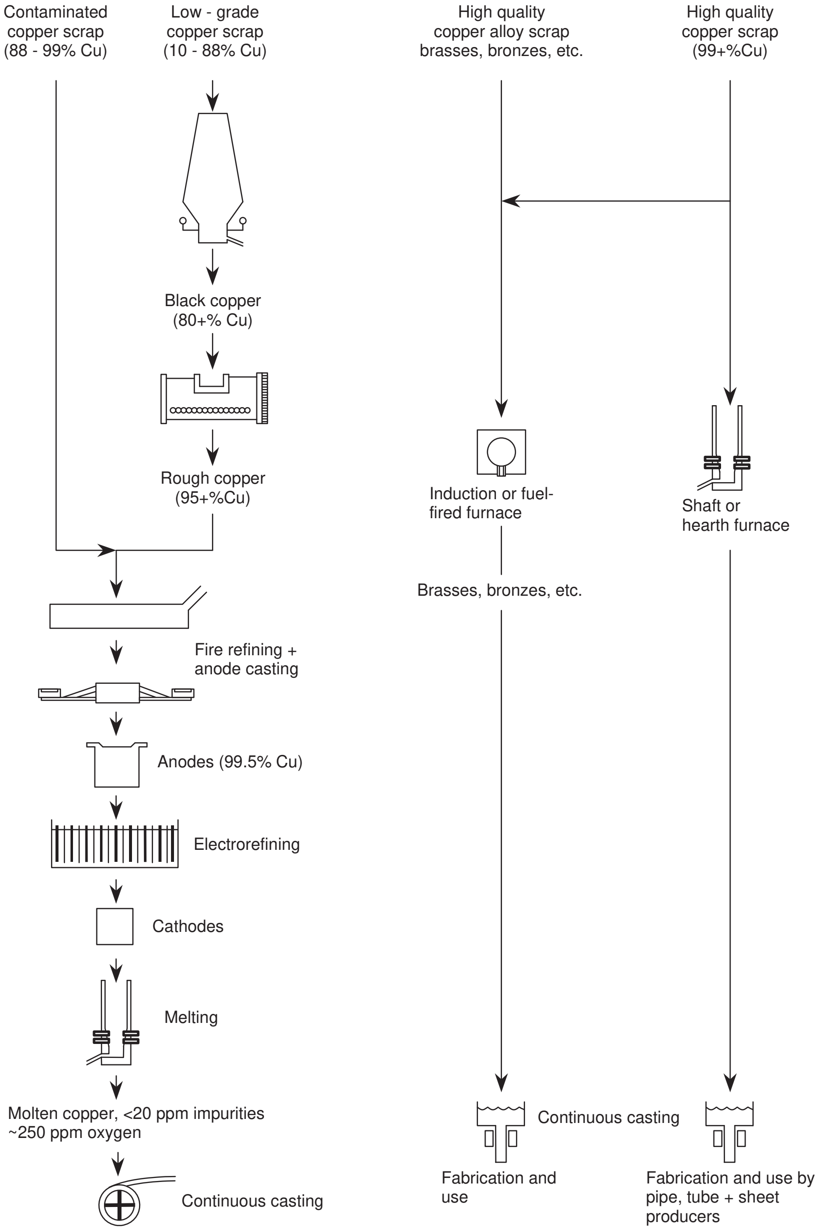

Figure 1.11 Flowsheet of processes for recovering copper and copper alloys from scrap. Low-grade scrap is usually smelted in shaft furnaces but other furnaces (e.g., electric) are also used.

Processing and manufacturing also produce copper and alloy scrap, called *new scrap*. Most of this scrap is easily recovered by internal recycle.

Production of copper from scrap (a) requires considerably less energy than mining and processing of copper ore; (b) minimizes carbon emissions; (c) avoids mine, concentrator, leach, and smelter wastes; and (d) helps to ensure the availability of copper for future generations.

The treatment given to copper scrap depends on its purity, Fig. 1.10. The lowest grade scrap is smelted and refined like concentrate in primary or secondary (scrap) smelters/refineries. Higher-grade scrap is fire-refined then electrorefined. The highest-grade scrap (mainly manufacturing waste) is often melted and cast without refining. Its copper is used for nonelectrical products, including tube, sheet, and alloys.

Alloy scrap (brass, bronze) is melted and cast as alloy. There is no advantage to separating it into pure metals. Some slagging is done during melting to remove dirt and other contaminants. The product alloy composition is adjusted by combining alloy and individual metal scrap as needed.

1.7 Safety

Of paramount concern in copper mining—manufacturing operations is safety (Mathis & Galloway, 2016). A safe working environment is fostered by

(a) setting an accident-free workplace as a primary goal
(b) close attention to safety by management, even in tough economic times
(c) inclusion of safety considerations during design and construction
(d) thorough worker safety training with regular updates
(e) mandatory wearing of safety apparel, such as steel-toed boots and hard hats
(f) effective lighting in all work areas, especially underground
(g) thorough maintenance and hazard identification/elimination
(h) thorough investigation of any accident or near-miss and resolution of any indicated problems
(i) "stay safe" discussions before every work shift
(j) personal responsibility for safety
(k) three-point contact when ascending or descending stairs and ladders.

Detailed safety concerns in various segments of copper making (e.g., smelting) are presented in later chapters. Safety excellence is detailed in *STEPS to Safety Culture Excellence* (Mathis & Galloway, 2013).

1.8 Environment

Production of pure metallic copper from mineral deposits (mines) involves many steps, including mining, concentration, smelting, leaching, and electrorefining or electrowinning, as well as land and water transportation.

Mining raises dust during blasting and trucking. It also alters the landscape by removing material from the surface and dumping waste rock in piles around the mine.

Concentration raises dust during crushing and produces small-particle tailings waste during concentration. Most concentrators minimize water use and contamination by recycling as much water as possible from the tailing ponds.

Smelting produces SO_2-bearing offgas. Fortunately, processes have been developed to capture this $SO_2(g)$ and make it into sulfuric acid, itself a valuable product. Smelters also produce solidified oxide slag which, in some locations, is a valuable abrasive and cement-making raw material.

Heap leaching alters the landscape by placing ore on the earth's surface and acid leaching it in the open. Extreme caution must be taken to prevent the acid from reaching the water table.

Electrorefining and electrowinning are contained in buildings, so their impact on the environment is not large. Generation of sulfuric acid mist above the electrolytic cells can adversely affect the working environment. Covering the cells and providing effective extraction fans ameliorates this problem. Well-designed workplace clothing and equipment are also essential. An important example is filtered breathing equipment for employees. These issues are discussed in depth in their specific chapters.

Beyond legal requirements, an important goal of the copper industry is to produce pure copper while minimizing deleterious effects on the environment. In 2020, this is a top goal of copper management and employees. Post-mine-life landscape rehabilitation is an important part of attaining this goal. Several videos describe rehabilitation (Hanson, 2016; Munsey, 2015; Teck Resources Limited, 2016).

1.9 Summary

About 80% of the world's primary copper is produced by concentration, smelting, and refining of sulfide ores. The other 20% is produced by heap leaching, solvent extraction, and electrowinning of oxidized and chalcocite ores. Secondary copper production from recycled end-of-use objects is 15%–20% of primary copper production (ICSG, 2018).

Electrochemical processing is always used to produce high-purity copper: electrorefining in the case of pyrometallurgical extraction and electrowinning in the case of hydrometallurgical extraction. The principal final copper product is Grade 1 copper ($\sim$250 ppm oxygen and $<$20 ppm unwanted impurities). It is suitable for nearly all uses.

The trend in copper extraction is toward processes that do not harm the environment and consume less energy and water. This has led to

(a) energy- and pollution-efficient oxygen-enriched smelting
(b) efficient recovery of $SO_2(g)$ from smelter offgas as sulfuric acid
(c) leaching–solvent extraction–electrowinning flowsheets
(d) increased water recycle
(e) increased recycle of end-of-use scrap
(f) reclamation of end-of-life mines and hydrometallurgical leach sites.

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CHAPTER 2

Production and use

Metallic copper occasionally occurs in nature. For this reason, it has been known to man since about 10,000 B.C. (Copper Development Association, 2020). Its early uses were in jewelry, utensils, tools, and weapons. Although its use gradually increased over the years, it was only in the 20th century, with the global adoption of electricity, that copper usage really expanded. Copper is essential to economic and technological development, so substantial growth in its applications has continued in the 21st century, driven by the rapid industrialization of China and other emerging-market economies (Fig. 2.1).

This chapter discusses production and use of copper around the world. It gives production, use and price statistics, and identifies and locates the world's largest copper-producing plants.

2.1 Properties and uses of copper

Copper is an excellent conductor of electricity and heat. It also resists corrosion. It is easily fabricated into wire, pipe, and other forms, and is easily joined by soldering and brazing. It is also malleable, ductile, and tough (not brittle). All of these properties are widely exploited (Table 2.1).

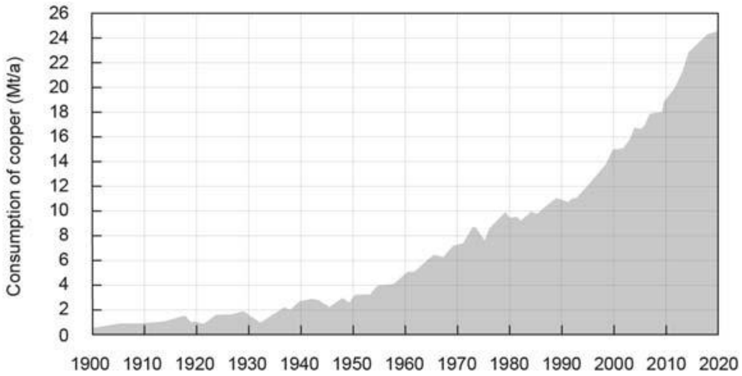

Figure 2.1 World use of refined copper, which has grown from less than 500,000 t in 1900 to more than 24.5 million tons in 2018, representing a compound annual growth rate of 3.4% (International Copper Study Group, 2019).

Extractive Metallurgy of Copper, Sixth Edition
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Table 2.1 Properties of copper (Copper Development Association, 2020).

Exploited property	% of use
Electrical conductivity	65
Corrosion resistance	16
Thermal conductivity	11
Mechanical and structural	6
Aesthetics	2

Copper is readily alloyed with zinc, tin, nickel, and other metals to improve its castability, strength, and corrosion resistance. Brass (Cu–Zn alloy) is an especially useful alloy that has a low solidification temperature and high fluidity, allowing efficient casting into intricate shapes. Beryllium–copper is heat treatable, is as hard and strong as steel, and can be used for several applications (Materion, 2020). Alloys account for about 25% of copper usage.

Among its significant beneficial properties, copper

- is easily drawn into extremely fine wire;
- is easily extruded into thin pipe and other shapes;
- is easily machined and threaded;
- is readily cast into intricate shapes, especially in alloy form;
- is antibacterial (useful in medical piping and other equipment);
- is nonmagnetic;
- has an attractive sheen and color;
- exhibits low metal-against-metal friction (in alloy form);
- has catalytic properties; and
- does not oxidize during use, so has a long service life and can be recycled without loss.

Fig. 2.2 shows the distribution of copper usage in various industries (International Copper Study Group, 2019). Its major use is in conduction of electricity, ranging from small domestic installations to high-voltage heavy-current applications. It is widely used in generators, motors, transformers, and in renewable energy. Its other major use today is in communication technologies, such as high-speed data transmission, area networks, cellphones, personal computers, and other electronic equipment. Copper can be used in construction for building wire, plumbing, and heating and refrigeration, as well as for its aesthetic appeal. Use of copper-based building materials in regions with high seismic activity can limit earthquake damage owing to its ability to absorb energy.

Its durability, machinability, and ability to be cast with high precision makes copper suitable for the manufacture of industrial equipment, such as gears, bearings, and turbine blades, and for use in the transport industry, including aircraft, high-speed rail, and vehicles. Its excellent heat-transfer properties find use in heat exchangers and pressure vessels. Copper and its alloys are widely used in marine environments, owing to good corrosion

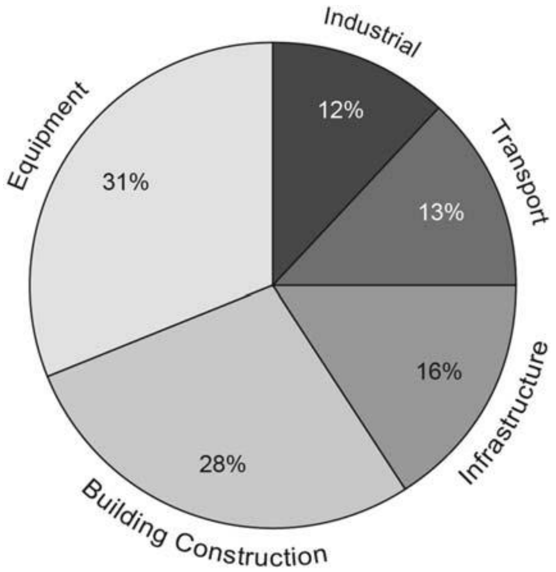

Figure 2.2 Major uses of copper by main industry (International Copper Study Group, 2019).

resistance. Copper also exhibits antimicrobial properties, which make it suitable for selected medical applications and for high-use surfaces, such as door knobs.

2.2 Global copper production

Fig. 2.3 shows global copper mine production. Mine output was almost 21 million tonnes in 2019 (International Copper Study Group, 2020), most of which was in the

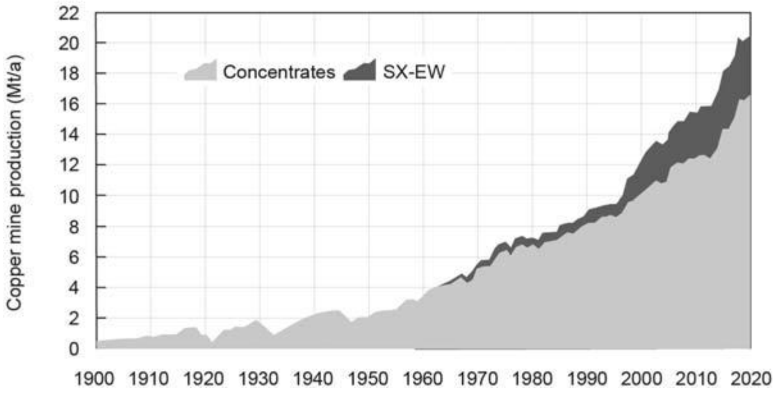

Figure 2.3 World copper mine production from 1900 to 2018. Hydrometallurgical production of copper only started to become significant in the 1970s, and today represents about 20% of global production (International Copper Study Group, 2019).

Table 2.2 Major world producers of copper in 2019, kt of contained copper (International Copper Study Group, 2020).

Country	% of total	Mine production (kt Cu)
Chile	34.8	5787
Peru	14.8	2455
China	10.1	1684
United States	7.7	1284
Democratic Republic of Congo	7.7	1283
Australia	5.6	929
Zambia	4.8	797
Russian Federation	4.8	791
Mexico	4.6	769
Kazakhstan	4.2	696
Canada	3.4	573
Poland	2.4	399
Brazil	2.2	362
Indonesia	2.2	361

form of concentrates (see Chapter 3); about 20% of mine production uses hydrometallurgical processing involving solvent extraction and electrowinning (SX—EW) of copper cathode (Chapters 15 and 16).

The Andes mountain region of South America (Chile and Peru) is the world's largest source of copper, accounting for about one-third of global output (Table 2.2). China and the United States of America are major producers, followed by the African Copper belt (Democratic Republic of Congo (DRC) and Zambia). The remaining production is scattered around the world. The world's 20 largest mines are listed in Table 2.3 and plotted in Fig. 2.4.

2.3 Copper minerals, mines, and cut-off grades

Table 2.4 lists the main copper minerals. These minerals occur at low concentrations in ores. The remainder of the ore is mostly oxide rock, such as quartz and potassium feldspar, with a small amount of waste sulfide minerals, such as pyrite.

A copper mine consists of regions of (i) ore, containing economic quantities of Cu minerals, and (ii) waste rock, containing low, uneconomic quantities of Cu minerals. These regions are located by drilling, sampling, and analyzing drill core for Cu. Where possible, the waste rock is not mined. Where the ore and rock are intertwined, they must be mined together and separated later, as described in Chapters 3 and 4.

Mined Cu ore typically contains 0.5% Cu (open-pit mines) and 2% Cu (underground mines). Many Cu ores also contain small amounts of valuable minor metals, such as gold,

Table 2.3 The world's 20 highest production Cu mines (International Copper Study Group, 2019). These account for about 40% of total world mined copper production.

	Mine	Country	Production (kt/a contained Cu)	Products
1	Escondida	Chile	1400	Concentrate and SXEW
2	Collahuasi	Chile	570	Concentrate and SXEW
3	Buenavista del Cobre	Mexico	525	Concentrate and SXEW
4	Morenci	United States	520	Concentrate and SXEW
5	Cerro Verde III	Peru	500	Concentrate
6	Antamina	Peru	450	Concentrate
7	Norilsk Polar Division	Russia	450	Concentrate
8	Las Bambas	Peru	430	Concentrate
9	El Teniente	Chile	422	Concentrate and SXEW
10	Chuquicamata	Chile	390	Concentrate and SXEW
11	Los Bronces	Chile	390	Concentrate and SXEW
12	Los Pelambres	Chile	370	Concentrate
13	Kansanshi	Zambia	340	Concentrate and SXEW
14	Radomiro Tomić	Chile	330	Concentrate and SXEW
15	Grasberg	Indonesia	300	Concentrate
16	Kamoto	DRC	300	SXEW
17	Bingham Canyon	United States	280	Concentrate
18	Toquepala	Peru	265	Concentrate and SXEW
19	Sentinel	Zambia	250	Concentrate
20	Olympic Dam	Australia	225	Concentrate and SXEW

DRC, Democratic Republic of Congo.

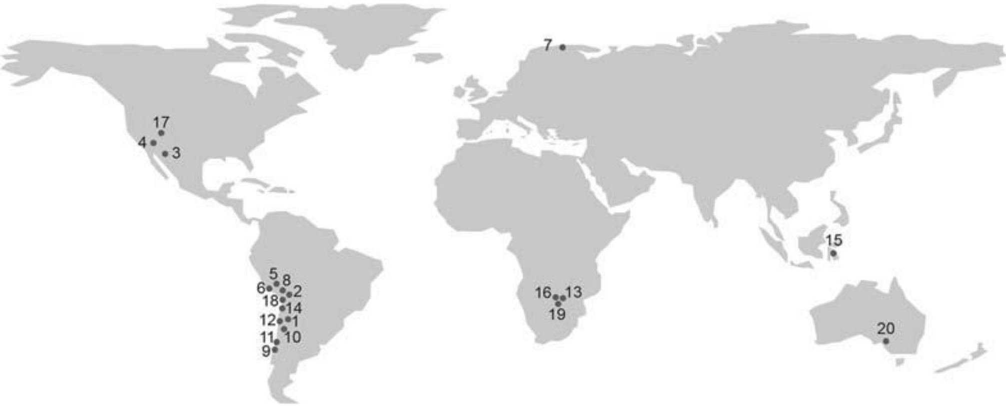

Figure 2.4 Map showing the location of the world's largest copper mines. The numbers refer to the data in Table 2.3. Notice the density of mines in the Chilean and Peruvian Andes mountains. Most are porphyry copper deposits (International Copper Study Group, 2019).

Table 2.4 Main commercial copper minerals. Chalcopyrite is by far the largest source of copper. Sulfide minerals are treated by pyrometallurgical processing (Fig. 1.1); carbonates, chlorides, oxides, silicates, and sulfates are treated by hydrometallurgical processing (Fig. 1.2), although secondary sulfides, e.g. chalcocite are increasingly being in this manner (see Chapter 14).

Type	Common minerals	Chemical formula	Theoretical % Cu
Primary sulfides			
Hypogene sulfides	Chalcopyrite	$CuFeS_2$	34.6
	Bornite	Cu_5FeS_4	63.3
Secondary minerals			
Supergene sulfides	Chalcocite	Cu_2S	79.9
	Covellite	CuS	66.5
	Digenite	$Cu_{1.8}S$	78.1
Native copper	Metal	Cu	100
Carbonates	Malachite	$CuCO_3 \cdot Cu(OH)_2$	57.5
	Azurite	$(CuCO_3)_2 \cdot Cu(OH)_2$	55.3
Hydroxysilicates	Chrysocolla	$CuO \cdot SiO_2 \cdot 2H_2O$	36.2
Oxides	Cuprite	Cu_2O	88.8
	Tenorite	CuO	79.9
Sulfates	Antlerite	$CuSO_4 \cdot 2Cu(OH)_2$	53.7
	Brochantite	$CuSO_4 \cdot 3Cu(OH)_2$	56.2

silver, molybdenum, rhenium, and cobalt, which can be profitably recovered during processing. Custom smelters can profit from the recovery of nickel, selenium, tin, zinc, and lead that is present in copper concentrates.

The average grade of ore that is extracted from any given mine is determined by the *cut-off grade* (% Cu). This value determines the split between materials classified as *ore* from that considered *waste*. Material with a copper content of less than the cut-off grade cannot be profitably treated for copper recovery and is considered waste. It is removed to large waste dumps.

Cut-off grade depends on the current copper selling price and the mining and extraction costs. If, for example, the price of copper rises and costs are constant, it may become profitable to treat lower-grade material. This means that cut-off grade (and average ore grade) will decrease. Lower copper prices and increased costs have the opposite effect. Higher levels of gold, silver, and molybdenum extraction decrease Cu cut-off grade because these elements provide additional income per tonne of ore.

Average world Cu ore grades (%Cu) are falling at about 25% per decade as copper-rich mines become depleted and newly located deposits contain less copper (Calvo et al., 2016). As shown in Fig. 2.5, it is now rare to find a large copper deposit averaging more than 1% or 2% Cu; furthermore, the mineralogy of new orebodies is becoming more

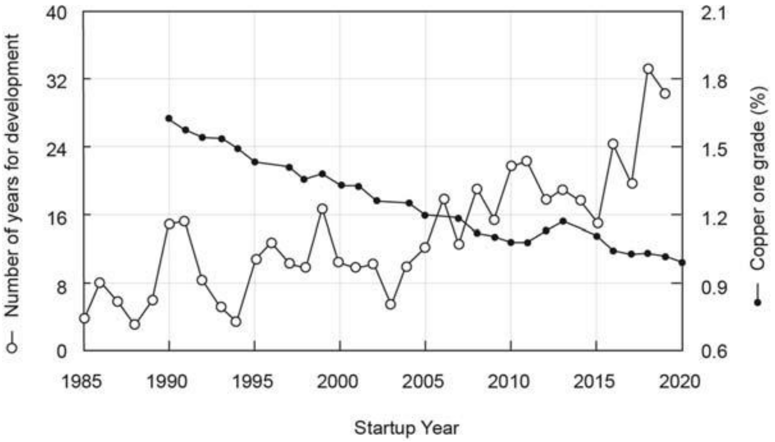

Figure 2.5 Trend of declining ore grade and increasing time to commercialization of copper deposits, owing to increasingly complex mineralogy of exploited copper ores. *(Adapted from Winton Group. (2017), Copper-bottomed booms and busts. Retrieved from https://www.winton.com/longer-view/copper-bottomed-booms-and-busts. Accessed 19 September 2020, with data from Brook Hunt.)*

complex and the time required from discovery of the deposit to commissioning of a mine has substantially increased (Winton Group, 2017).

2.4 Locations of processing plants

2.4.1 Smelters

The first stage of copper extraction from sulfide ores is production of high-grade (~25% Cu) particulate concentrate from low-grade (~0.5%–2% Cu) ore (Chapters 3 and 4). This is always done at the mine site to avoid costly long-distance transport of the ore's waste rock.

The resulting concentrate is usually transported by truck or train from the mine to a regional port, then by ship to coastal or riverside smelters around the world, located mainly in China, Japan, and Europe. China is by far the biggest importer, processing ~7000 kt/a of Cu-in-concentrate. Chile is by far the largest concentrate exporter, shipping out ~3000 kt/a of contained Cu.

The world's largest smelters are listed in Table 2.5 and their locations are shown in Fig. 2.6. In 2018, China accounted for about 40% of world smelter production, followed by Chile (10%) and Japan (7%).

2.4.2 Electrorefineries

The main product of smelting is copper anodes, which are treated in an electrorefinery to produce pure high-grade (<25 ppm impurities) copper cathode. Copper electrorefineries are usually built near the smelter that supplies them with anodes or in a convenient central

Table 2.5 The world's 20 largest Cu smelters in descending order of smelter capacity (International Copper Study Group, 2019). They account for about 60% of the world's primary copper production.

	Smelter	Country	Capacity (kt/a Cu)	Smelting process
1	Guixi	China	900	Metso Outotec flash
2	Birla	India	500	Metso Outotec flash, Mitsubishi
3	Chuquicamata	Chile	450	Metso Outotec flash + Teniente converter
4	Jinchuan (Fangchenggang)	China	450	Ausmelt® TSL Process – Metso Outotec + reverberatory
5	Hamburg	Germany	450	Metso Outotec flash, Contimelt, electric
6	Besshi/Ehime (Toyo)	Japan	450	Metso Outotec flash
7	Saganoseki/Ooita	Japan	450	Metso Outotec flash
8	El Teniente (Caletones)	Chile	400	Reverberatory + Teniente converter
9	Jinchuan	China	400	Reverberatory + Kaldo converter
10	Jinchuan	China	400	Metso Outotec flash
11	Jinlong (Tongdu)	China	400	Metso Outotec flash
12	Xiangguang	China	400	Metso Outotec flash
13	Sterlite (Tuticorin)	India	400	Isasmelt
14	Norilsk (Mikelevy, Medny)	Russia	400	Reverberatory, electric, Vanyukov
15	Pirdop	Bulgaria	360	Metso Outotec flash
16	Ilo	Peru	360	ISASMELT™
17	Onahama/Fukushima	Japan	354	Mitsubishi + Reverberatory
18	Naoshima/Kagawa	Japan	342	Mitsubishi
19	Isabel/Leyte	Philippines	330	Metso Outotec flash
20	Huelva	Spain	320	Metso Outotec flash

Figure 2.6 Map showing the locations of the world's 20 largest copper smelters. The numbers refer to the data in Table 2.4. Notice the large concentrations in China and Japan. These smelters mostly import Cu concentrate from which they make Cu anodes.

Table 2.6 The world's 20 largest Cu refineries in descending order of copper production capacity (International Copper Study Group, 2019). They account for about 60% of the world's refined copper production.

	Refinery	Country	Capacity (kt/a Cu)
1	Guixi	China	1000
2	Jinchuan	China	650
3	Daye/Hubei	China	600
4	Yunnan	China	500
5	Birla	India	500
6	Jinchuan	China	450
7	Toyo/Niihama (Besshi)	Japan	450
8	Amarillo	United States	450
9	Chuquicamata	Chile	450
10	Onsan I	Korea	440
11	Hamburg	Germany	416
12	El Paso	United States	415
13	Las Ventanas	Chile	410
14	Jinguan	China	400
15	Jinlong (Tongdu)	China	400
16	Xiangguang	China	400
17	Shandong Fangyuan	China	400
18	Sterlite	India	400
19	Pyshma	Russia	390
20	Canadian Copper Refinery	Canada	370

location close to several smelters. There is also a small amount of world trade in anodes (International Copper Study Group, 2017), which favors coastal and riverside electrorefineries. The world's largest electrorefineries are listed in Table 2.6 and shown in Fig. 2.7.

2.4.3 Hydrometallurgical plants

Leach–SX–EW operations are always located next to their mines. This is because ores that are suitable for leaching are low in copper grade, and hence uneconomic to transport. The world's largest copper leach–SX–EW operations are listed in Table 2.7 and their locations are shown in Fig. 2.8. This technology dominates in Chile and the African Copper Belt.

2.5 Price of copper

Fig. 2.9 shows the price of copper from 1958 to 2020. The dollar price increased steadily until 2002 then rose rapidly, reaching record high values in 2011. The post-2005 high prices were due to the huge demand for copper by China during its rapid industrialization and infrastructure growth. The large swings in price since then are mostly the result of short-term variations in Chinese demand, with some due to arbitrary U.S. tariffs.

Figure 2.7 Map showing the locations of the world's 20 largest copper electrorefineries. The numbers refer to the data in Table 2.5. The large number of electrorefineries in China is due to its rapid growth of electrical infrastructure and other industrial and consumer expansions.

Table 2.7 The world's 20 largest Cu solvent extraction—electrowinning plants in descending size (International Copper Study Group, 2017, 2018). These plants account for almost 70% of the world's electrowon copper production.

	SXEW Refinery	Country	Capacity (kt/a Cu)
1	Morenci	United States	350
2	Escondida	Chile	270
3	Radomiro Tomić	Chile	220
4	Mutanda	DRC	220
5	Tenke Fungurume	DRC	214
6	Buenavista del Cobre	Mexico	175
7	Kamoto	DRC	165
8	Spence	Chile	160
9	El Abra	Chile	150
10	Konkola	Zambia	130
11	Dikuluwe	DRC	125
12	Gabriella Mistral	Chile	120
13	Safford	United States	110
14	Zaldivar	Chile	100
15	Sepon	Laos	90
16	Antucoya	Chile	85
17	Chuquicamata	Chile	80
18	Kinsevere	DRC	80
19	Lomas Bayas	Chile	75
20	Centinela	Chile	70

DRC, Democratic Republic of Congo.

2.6 Future outlook

China, which accounts for more than half of world copper consumption, is currently developing several megacities and high-speed rail networks that will require large amounts of copper (Winton Group, 2017). The increasing role of renewable energy

Figure 2.8 Map showing the locations of the world's 20 largest copper solvent extraction—electrowinning plants. Most of these are in Chile and the African Copper Belt. The numbers refer to the data in Table 2.6.

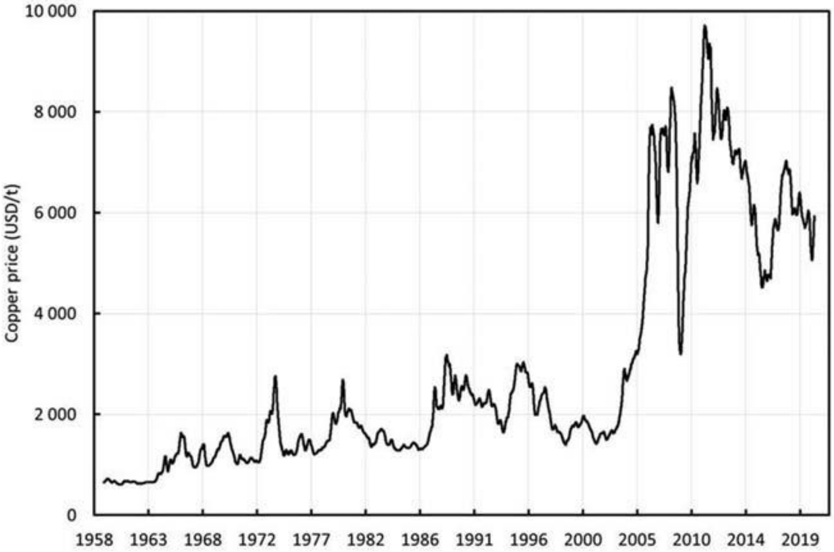

Figure 2.9 London Metal Exchange cash price for Grade A copper since 1958. The price climbed rapidly from 2002 owing to the rapid industrialization of China. Specifications for Grade A copper are given in Chapter 13. *(Data from Macrotrends. (2020). Copper prices — 45 year historical chart. Retrieved from https://www.macrotrends.net/1476/copper-prices-historical-chart-data. Accessed 19 September 2020.)*

will also boost consumption because wind turbines and solar panels require larger amounts of copper, per unit of energy generated, than traditional coal and gas plants. Electric and hybrid cars also use considerably more copper than conventional vehicles (International Copper Study Group, 2019).

2.7 Summary

Copper is produced around the world. About 40% is mined in the western mountain region of South America. Mined ore grades (%Cu) have fallen over the years as today's relatively high Cu grade deposits are mined out and newly discovered deposits contain smaller amounts of Cu.

Concentrators and leach—solvent extraction—electrowinning plants are located near their mines. Smelters and refineries are increasingly located near sea ports so that they can receive concentrates from mines around the world.

Copper's most exploited property is its high electrical conductivity, in conjunction with its excellent corrosion resistance, formability, and joinability. Its high thermal conductivity and corrosion resistance are also exploited in many heat transfer applications. Copper is readily alloyed with other metals (mostly zinc) to make complex, strong, corrosion-resistant castings.

Worldwide, about 21 million tonnes of copper are mined each year. Currently, about one-third of copper is recycled at the end of its useful life (Statistica, 2020) (Chapter 18), which adds an additional 5 million tonnes into the market.

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CHAPTER 3

Production of high copper concentrates—comminution and flotation (Johnson et al., 2019)

The grade of copper ores is typically too low (0.5%–2% Cu) for economic direct smelting. Heating and melting the huge quantity of largely worthless rock would require too much energy and too much furnace capacity. For this reason, all ores destined for pyrometallurgical processing are physically concentrated before smelting. The product of this step is *concentrate*, which contains ∼30% Cu (virtually all as sulfide minerals).

Ores destined for hydrometallurgical processing are rarely concentrated. Cu is usually extracted from these ores by direct leaching of crushed or milled ore (Chapter 14).

This chapter describes the production of high-grade concentrate from low-grade ore. Processing of sulfide minerals is emphasized because these minerals account for virtually all Cu concentration.

3.1 Concentration flowsheet

Concentration of Cu ores consists of isolating the copper—containing minerals from the rest of the ore. It entails the following:

(a) blasting, crushing, and grinding the ore to a size where the Cu mineral grains are liberated from the non-Cu mineral grains, known as *comminution*, and

(b) physically separating the liberated Cu minerals from non-Cu minerals by *froth flotation* to generate a Cu-rich concentrate and Cu-barren *tailings* Chapter 4.

Fig. 1.2 shows these processes in relation to the overall copper-making flowsheet. Figs. 3.1 and 3.11 describe them in detail.

Copper concentrators typically treat 10,000–150,000 tonnes of ore per day, depending on the production rate of their mines (ICSG, 2010).

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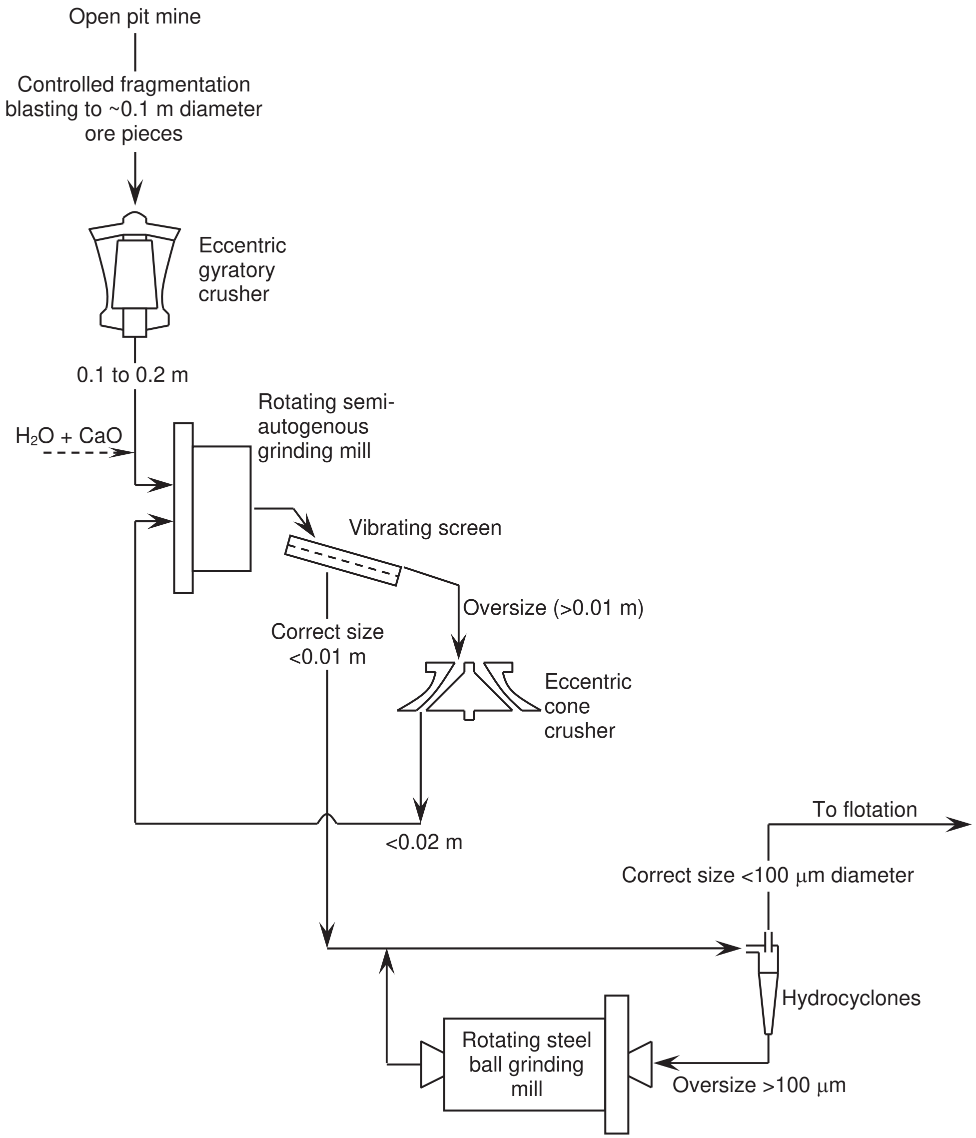

Figure 3.1 Flowsheet for preparing small flotation feed particles from as-mined ore fragments. One stage of crushing and two stages of grinding are shown. The crushing is open-circuit, i.e., there is no recycle loop. The two grinding circuits are closed circuit, i.e., oversize material is recycled for recrushing or regrinding to specified particle sizes. *(International Copper Study Group (ICSG) World Copper Factbook, IWCC and ICA.)*

3.2 The comminution process

To liberate the copper-containing minerals from the gangue materials in the ore (Chapter 2) and enable them to be collected by flotation into a concentrate, the ore should be finely ground.

Comminution is performed in three stages:

(a) *breaking* the ore by explosions in the mine (blasting);
(b) *crushing* large ore pieces by compression in gyratory or roll crushers; and
(c) wet *grinding* of the crushed ore in rotating tumbling mills, where abrasion, impact, and compression all contribute to breaking the ore.

The final fineness of grind is mainly determined by the number of times an ore particle passes through the grinding mills. Separate crushing and grinding steps are necessary because it is not possible to break massive run-of-mine ore pieces while at the same time controlling the fineness of grind that is necessary for the flotation step.

3.2.1 Crushing

Crushing is mostly done in the mine, mostly using *gyratory crushers* (Bearman, 2019, Fig. 3.2). This permits ore to be transported out of an open-pit mine by conveyor. It also permits easy hoisting of ore out of an underground mine. The crushed ore is stored in a coarse-ore stockpile, from which it is sent by conveyor to a grinding mill. The ore from crushing is then sent for grinding.

3.2.2 Grinding

3.2.2.1 Grind size and liberation of copper minerals

To isolate the copper-containing minerals into a concentrate, the ore should be finely enough ground to liberate the Cu mineral grains from the non-Cu mineral grains. The extent of grinding required to do this is determined by the size of mineral grains in the ore. Laboratory-scale flotation tests on materials of different particle sizes are usually required to determine the grind size that is required to liberate the copper minerals.

Fig. 3.3A shows the effect of grind size on recovery of Cu into the concentrate, while Fig. 3.3B shows the corresponding Cu concentration in the tailings. There is an optimum grind size for maximum recovery of Cu to the concentrate in the subsequent flotation step. Too large a grind size causes some Cu mineral grains to remain combined with or *occluded* by non-Cu mineral grains, preventing their flotation; too fine a grind size causes the rising bubbles in the flotation process to push the very tiny Cu-containing particles aside, preventing their contact with the bubble and reducing their recovery to the concentrate. In addition, very fine rock and Fe-sulfide mineral particles may agglomerate with very fine Cu-sulfide particles, preventing them from floating.

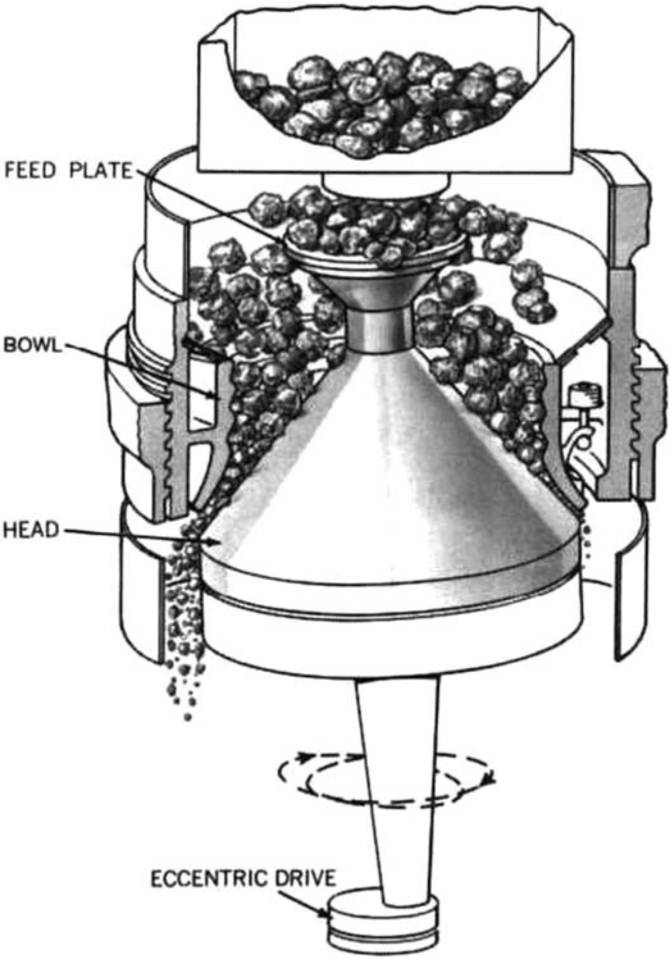

Figure 3.2 Gyratory crusher for crushing as-mined ore to ~0.2 m diameter pieces. The crushing is done by compression of ore pieces between the eccentrically rotating spindle and the fixed crusher wall. The crushing surface on the spindle can be up to 3 m high, 1.5 m diameter. Crushing rates are 10,000—150,000 tonnes of ore per day. *(International Copper Study Group (ICSG) World Copper Factbook, IWCC and ICA.)*

Liberation of mineral grains from each other generally requires grinding to ~100 μm diameter particle size. Flotation begins to be adversely affected when particles less than ~10 μm are produced.

Grinding requires considerable electrical energy (Table 3.1). This is another reason to avoid overgrinding.

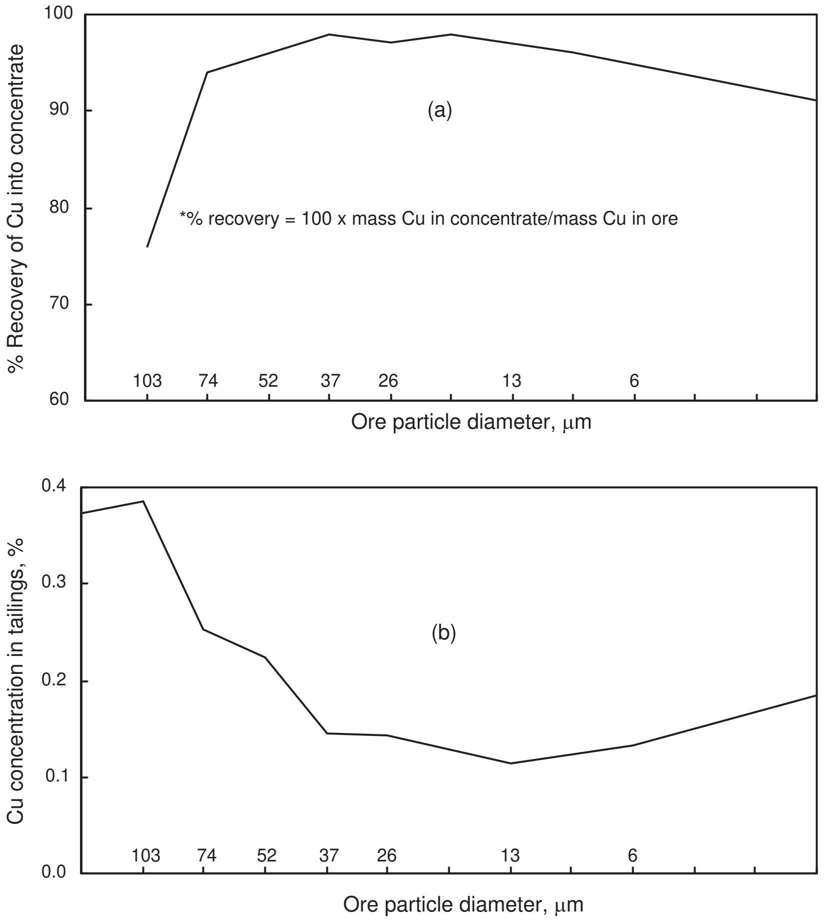

Figure 3.3 Effect of grind particle size on (A) Cu recovery to concentrate and (B) % Cu in tailings. The presence of an optimum is shown (Taggart, 1954). *(International Copper Study Group (ICSG) World Copper Factbook, IWCC and ICA.)*

3.2.2.2 Grinding equipment

Grinding produces ore particles of sufficient fineness for Cu mineral recovery by flotation. The most common grinding mills are *semiautogenous* (*SAG*) and *autogenous* (*AG*) mills and cone mills (Fig. 3.4; Giblett, 2019; Jones & Pena, 1999). A grinding circuit usually consists of one SAG or AG mill and one or two cone mills. Grinding is continuous and fully integrated with the subsequent flotation operation. Grinding is always done wet, with mixtures of ~70 mass% solids in water.

3.2.2.3 Autogenous and semiautogenous mills

The crusher product is ground in an SAG or AG mill (Giblett, 2019). AG mills crush the ore without the need for iron or steel grinding media. They are used when the ore is hard

Table 3.1a Industrial crushing and grinding data for three copper concentrators. They all treat ore from large open-pit mines. Flotation details are given in Table 3.5.

Concentrator	Candelaria, Chile	El Soldado, Chile	Los Bronces, Chile
Ore treated per year, tonnes	25,000,000 (2001)	7,700,000 (2010)	21,000,000 (2010)
Ore grade, %Cu	0.9–1.0	0.63	1.055
Crushing		Chalcopyrite	Chalcopyrite
Primary gyratory Crusher	1	1	1
Diameter × height, m	1.52 × 2.26	1.1 × 1.65	1.4 × 1.9
Power rating, kW	522	300	430
Rotation speed, RPM			6.5
Product size, m	0.1–0.13	0.2	0.2
Energy consumption, kWh per tonne of ore	0.3 (estimate)	0.2	0.25 (0.18 m diameter product
Secondary crushers	No	Yes, 4	No
First stage grinding			
Mill type	Semiautogenous	Semiautogenous	Semiautogenous
Number of mills	2	1	2
Diameter × length, m	11 × 4.6	10.4 × 5.2	8.5 × 4.3
Power rating each Mill, kWh	12,000	11,300	5590
Rotation speed, RPM	9.4–9.8	10.2	11.3
Vol. % "steel" in mill	12–15	15	13%–15%
Ball size, initial	12.5 cm	12.7	12.7
Ball consumption, kg per tonne of ore	0.3	0.32	0.35
Feed	70% ore, 30% H_2O	80% ore 20% water	70% ore 30% water
Product size	80% < 140 μm	200 μm	3 cm
Oversize treatment	22% ore recycle through two 525 kW crushers		Oversize to pebble crushers
Energy consumption, kWh per tonne of ore	7.82		6.5
Second stage grinding			
Mill type	Ball mills	Rod + ball mills	Ball mills
Number of mills	4	4 rod, 7 ball	3
Diameter × length, m	6 × 9	3.6 × 2.5	7 × 11
Power rating each Mill, kW	5600	Rod 350 Ball 550	10,800
Rotation speed, RPM		28	12
Vol. % "steel" in mill		47	35
Feed		70% ore, 30% w	65% ore, 35% water
Product size			80% < 212 μm

Table 3.1a Industrial crushing and grinding data for three copper concentrators. They all treat ore from large open-pit mines. Flotation details are given in Table 3.5.—cont'd

Concentrator	Candelaria, Chile	El Soldado, Chile	Los Bronces, Chile
Energy consumption, kWh per tonne of ore	7 (estimate)	∼8	7.2
Hydrocyclones	14 Krebs (0.5 m diameter)	14 (∼0.6 m diameter)	3 (Krebs + Cavex) (0.66 m diameter)
Particle size monitor		Yes PS1200	Yes PS1200

Table 3.1b Industrial crushing and grinding data for three copper concentrators, 2010. Flotation details are given in Table 3.5.

Concentrator	Africa, open pit	Africa, u-ground	Mantos Blancos, Chile
Ore treated per year, tonnes	4,000,000	900,000	4,500,000
Ore grade, %Cu	0.15	0.45	1.13
Crushing	Chalcocite, chalcopyrite	Chalcopyrite	Chalcocite
Primary gyratory Crusher	1 jaw crusher	1 jaw crusher	1
Diameter × height, m	4.2 × 6.5	8.5 × 11	1.1 × 1.65
Power rating, kW	250	132	300
Rotation speed, RPM			
Product size, m	80% < 0.25	80% < 0.25	0.15
Energy consumption, kWh per tonne of ore	5.4	4.5	0.4
Secondary crushers	None	Yes, jaw crusher	Yes, 4
First stage grinding			
Mill type	Semiautogenous	Semiautogenous	Ball mills
Number of mills	1	1	2
Diameter × length, m	8.53 × 4.35	6.1 × 2.75	3.8 × 4.6
Power rating each Mill, kWh	6000	1300	1120
Rotation speed, RPM	14	12	21.6
Vol. % "steel" in mill	22%	25%	38–40
Ball size, initial, cm	12.5	12.5	
Ball consumption, kg per tonne of ore	0.41	0.9	
Feed	85% ore, 15% water	85% ore, 15% water	84% ore, 16% water
Product size	80% < 800 μm	80% < 600 μm	75% < 212 μm
Oversize treatment	Pebble crushers, SAG	Recycle to SAG	
Energy consumption, kWh per tonne of ore	8.5	6.5	13.5

Continued

Table 3.1b Industrial crushing and grinding data for three copper concentrators, 2010. Flotation details are given in Table 3.5.—cont'd

Concentrator	Africa, open pit	Africa, u-ground	Mantos Blancos, Chile
Second stage grinding			
Mill type	Ball mill	Ball mill	Ball mill
Number of mills	1	1	1
Diameter × length, m	6.1 × 9.05	4.27 × 7.01	3.5 × 5.2
Power rating each Mill, kW	6000	1860	940
Rotation speed, RPM	18	16	23
Vol. % "steel" in mill	35%	32	38–40
Feed	85% ore, 15% water	85% ore, 15% water	85% ore, 15% water
Product size	80% < 125 μm	80% < 100 μm	75% < 212 μm
Energy consumption, kWh per tonne of ore	16.8	15	20
Hydrocyclones	8 (1.1 m dia)	8 (0.25 m dia)	5 (0.5 m diameter
Particle size monitor	Outotec PSI	Outotec PSI	

Table 3.1c Industrial crushing and grinding data for three copper concentrators, 2010. They all treat ore from large open-pit mines. Flotation details are given in Table 3.5.

Concentrator	Cerro Verde Peru	Ray, Arizona	Sierrita, U.S.A.
Ore treated per year, tonnes	3,900,000	10,000,000	34,000,000
Ore grade, %Cu	0.6 (chalcopyrite)	0.453 in Chalcopyrite and Chalcocite	0.23% Cu in cpy 0.03 Mo in MoS_2
Crushing			
Primary gyratory Crusher	1	1	2
Diameter × height, m	1.5 × 2.87	1.5 × 2.3	1.5 × 2.3
Power rating, kW	750		600
Rotation speed, RPM			
Product size, m	0.125	0.152trun -1	80% < 0.1
Energy consumption, kWh per tonne of ore	5		0.08
Secondary crushers	Yes	No	4
First stage grinding			
Mill type	Ball mills	Semiautogenous	Ball mills